Type Ia Supernovae are Excellent Standard Candles in the Near-Infrared

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Abstract

We use 89 Type Ia Supernovae (SN Ia) with optical and near-infrared (NIR) photometry to derive distances and create low redshift (z<0.04) Hubble diagrams. We explore both a Gaussian Process (GP) method and a mean Template method for fitting light curves (LCs) and we extract distances with a hierarchical Bayesian model that includes peculiar velocity and photometric uncertainties. For 56 SN Ia with both optical and NIR observations near max light, the GP method for the NIR LCs yields a Hubble-diagram intrinsic scatter of σ_{int} = 0.087 +/- 0.014 mag when referenced to NIR max and 0.090 +/- 0.014 mag, when referenced to B-max. ***For each NIR band, referencing to NIR-max versus B-max yields smaller intrinsic scatter and weighted RMS.*** Using NIR LC templates referenced to B-max yields a larger value of σ_{int} = 0.118 +/- 0.015 mag. Fitting the corresponding optical data using standard LC fitters that additionally use LC shape and color corrections, yields larger intrinsic scatter of σ_{int} = 0.148 +/- 0.022 with SALT2 and 0.128 +/- 0.018 with SNooPy. ***Applying our GP method to subsets of SN Ia NIR LCs at NIR max light, even without LC shape or host-galaxy dust reddening corrections, provides smaller intrinsic scatter in the inferred distances, at the ~2-3σ level, than standard optical methods that do correct for those effects.***

Near-Infrared Light Curve Templates

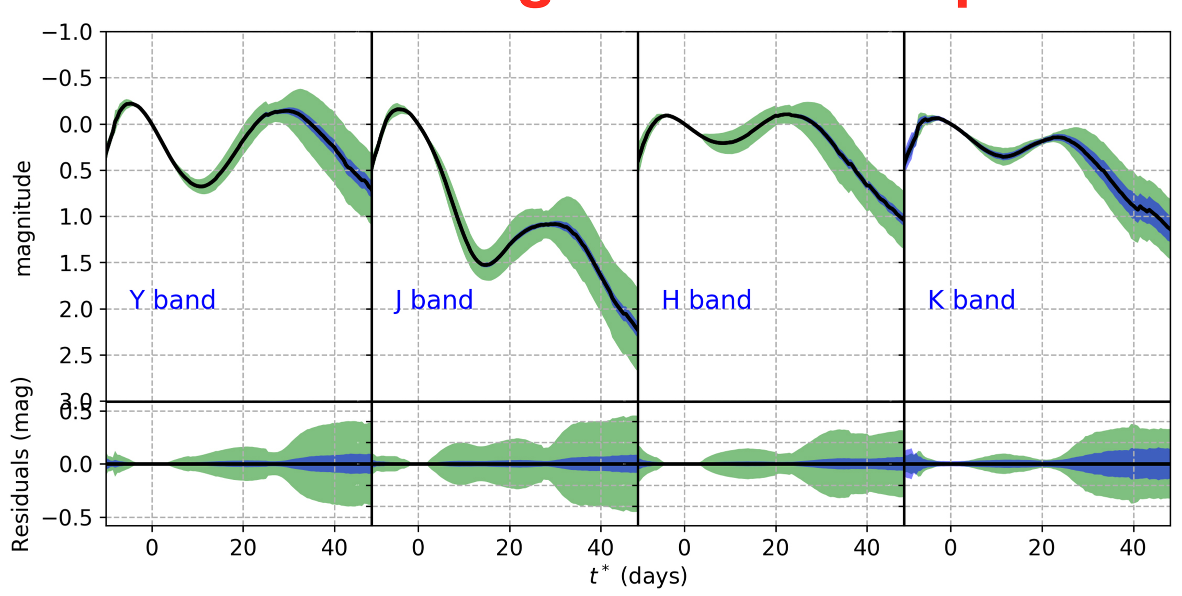

Fig 1. Normalized mean *YJHKs* templates with magnitude zero at t*= 0, (referenced to t_{Bmax}) and residuals. Plots show normalized mean magnitude M(t*) (black) vs. rest-frame phase t*, population standard deviation $\sigma_{M(t*)}$ (green) and the uncertainty in M(t*) (blue), from a hierarchical Bayesian model and Gaussian Process method.

NIR-Only Hubble Diagrams

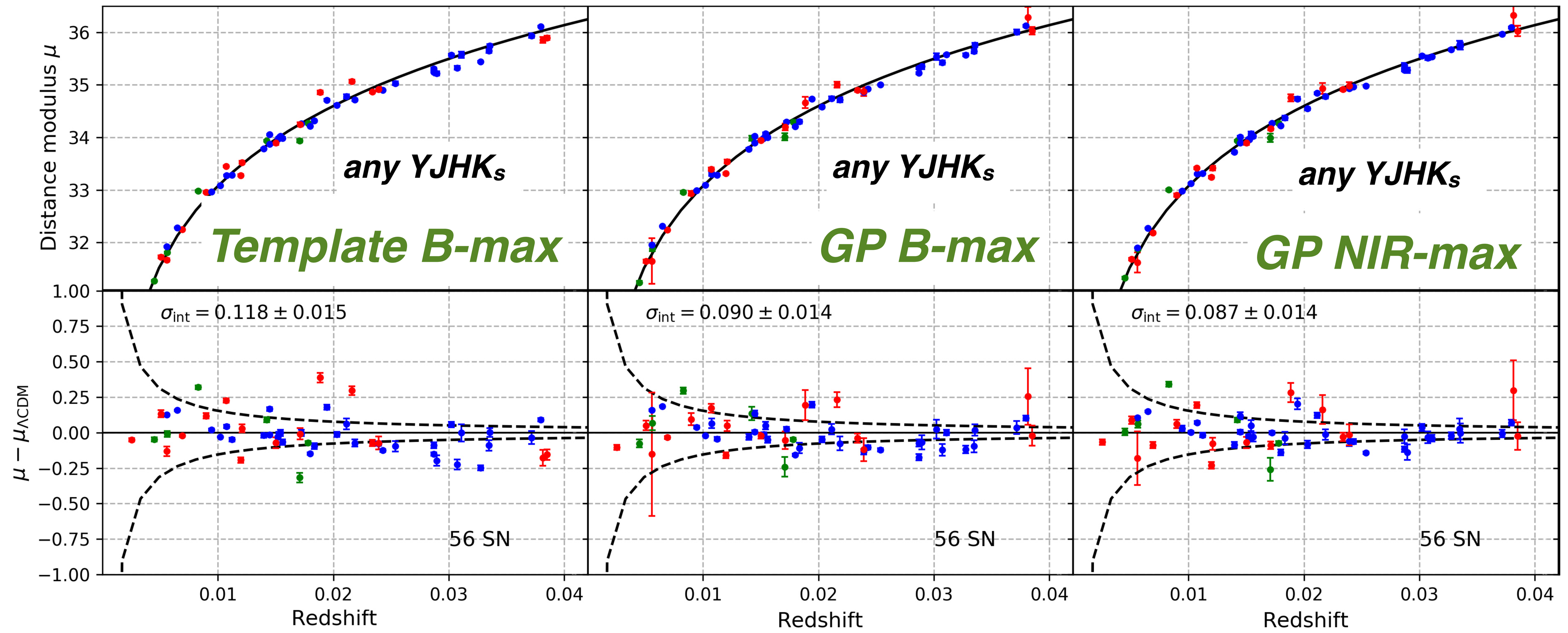

Fig 2. Any *YJHKs* Hubble diagrams (top), residuals (bottom) for: Template Method (*Left*) and GP Method referenced to t_{Bmax} (*Middle*) or $tNIR_{max}$ (*Right*). NIR LCs from: CfA (red; Wood-Vasey et al. 2008; Friedman et al. 2015), CSP (blue; Krisciunas et al. 2017), others (green). Template method yields larger intrinsic scatter for same SN Ia: σ_{int} = 0.118 +/- 0.015 mag vs. GP, which yields smaller intrinsic scatter at NIR max of σ_{int} = 0.087 +/- 0.014 mag than at t_{Bmax}, where σ_{int} =0.090 +/- 0.014 mag. Assumes peculiar velocity uncertainty $\sigma_{v,pec}$ =150km/s.

Light Curve Fit Methods

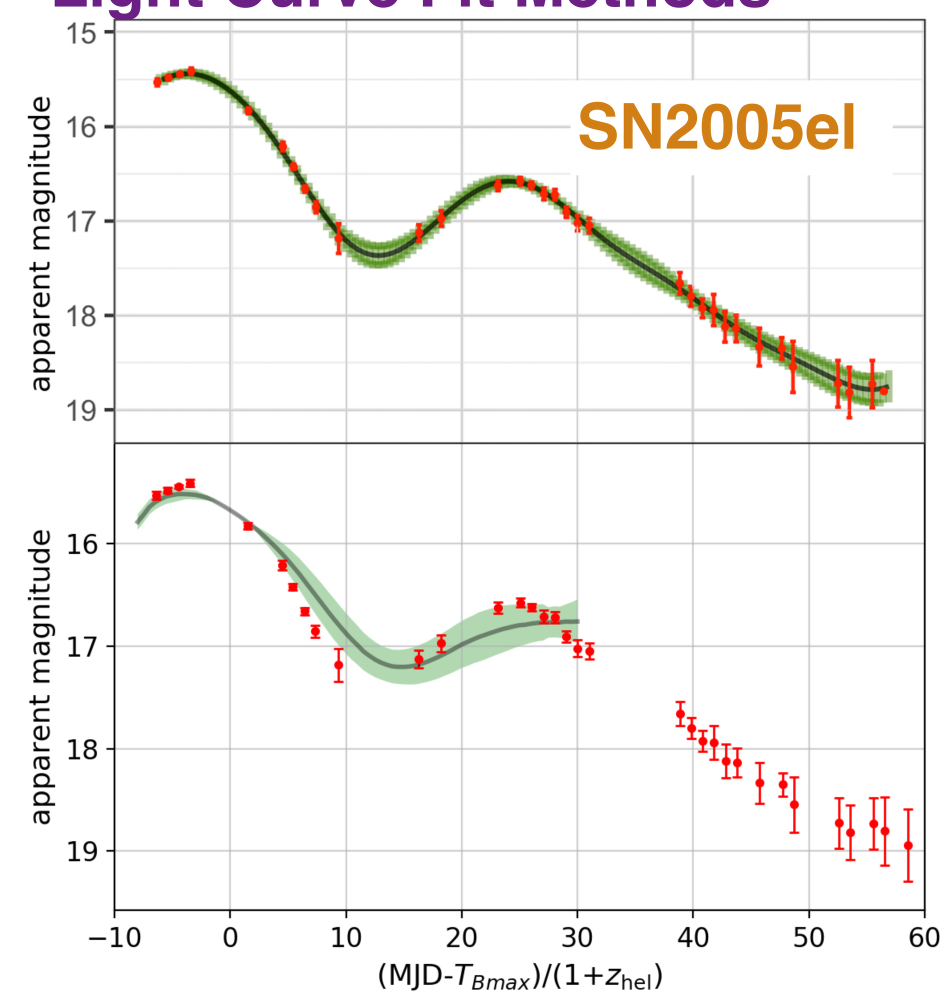

Fig 4. LC fits using the Gaussian Process method (top), requiring data near NIR max, and the Template method (bottom), which works for arbitrarily sampled data.

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NIR Intrinsic Scatter & Weighted RMS

Band	Method	N_{SN}	σ_{int} [mag]	wRMS [mag]
Y	Template	41	0.111 ± 0.019	0.132
Y	GP (NIR max)	29	0.065 ± 0.020	0.095
Y	GP (B max)	29	0.079 ± 0.019	0.107
J	Template	87	0.140 ± 0.016	0.164
J	GP (NIR max)	51	0.108 ± 0.018	0.134
J	GP (B max)	51	0.124 ± 0.019	0.154
H	Template	80	0.123 ± 0.016	0.155
H	GP (NIR max)	44	0.031 ± 0.027	0.094
H	GP (B max)	44	0.064 ± 0.020	0.112
K_s	Template	30	0.180 ± 0.033	0.214
K_s	GP (NIR max)	13	0.094 ± 0.057	0.157
K_s	GP (B max)	13	0.098 ± 0.055	0.157
any $YJHK_s$	Template	89	0.138 ± 0.014	0.150
any $YJHK_s$	**Template^a**	**56**	$\mathbf{0.118 \pm 0.015}$	**0.142**
any $YJHK_s$	**GP (NIR max)**	**56**	$\mathbf{0.087 \pm 0.014}$	**0.093**
any $YJHK_s$	**GP (B max)**	**56**	$\mathbf{0.090 \pm 0.014}$	**0.105**
JH	Template	80	0.134 ± 0.015	0.153
JH	GP (NIR max)	41	0.055 ± 0.019	0.096
JH	GP (B max)	41	0.081 ± 0.018	0.114
YJH	Template	37	0.101 ± 0.019	0.129
YJH	GP (NIR max)	21	0.052 ± 0.023	0.091
YJH	GP (B max)	21	0.073 ± 0.022	0.105
JHK_s	Template	28	0.151 ± 0.026	0.178
JHK_s	GP (NIR max)	11	0.032 ± 0.103	0.096
JHK_s	GP (B max)	11	0.086 ± 0.042	0.119
Optical BVR	**SALT2**	**56**	$\mathbf{0.148 \pm 0.022}$	**0.183**
Optical BVR	**SNooPy**	**56**	$\mathbf{0.128 \pm 0.018}$	**0.136**

Table 1. NIR intrinsic scatter, wRMS for Template, GP B-max, GP NIR max. Latter yields smaller σ_{int}, wRMS for all NIR sets. Optical *BVR* fits shown last.

Optical-Only Hubble Diagrams

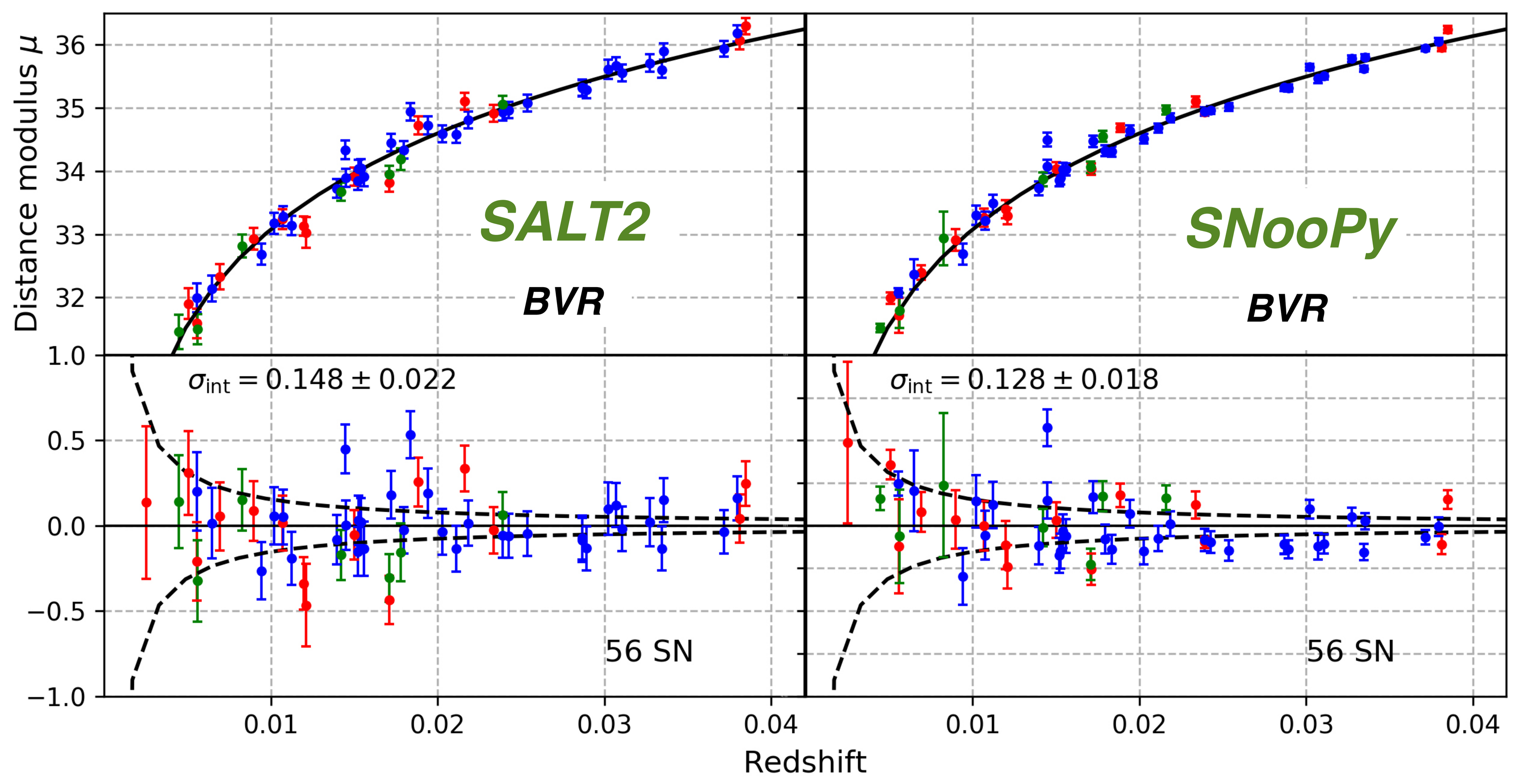

Fig 3. Same as Fig. 2 but using SALT2 and SNooPy to fit only optical *BVR* LCs for the same 56 SN Ia. The intrinsic scatter is ~2-3σ larger than for several GP *YJHKs* subsets at NIR max. See Tables 1-2.

Absolute Mags

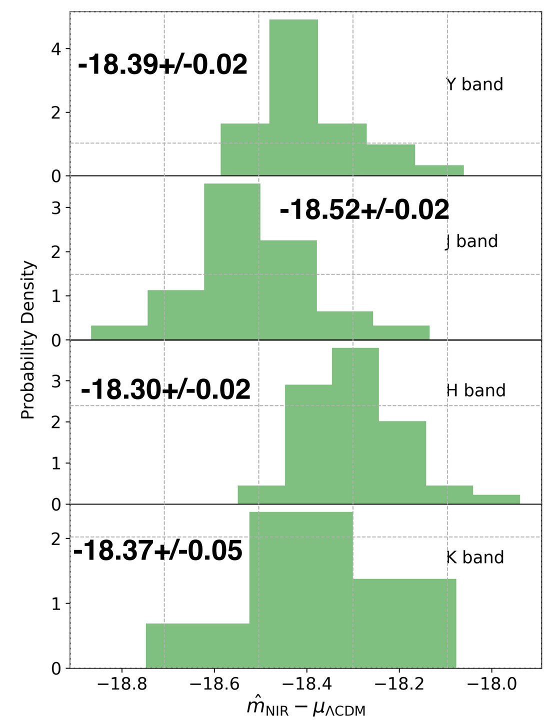

Fig 5. Absolute mag histograms: GP NIR max. *YJHKs* means shown.

Optical vs. NIR Intrinsic Scatter

Optical BVR - NIR band(s)	$\Delta\sigma_{int}$	n-σ
SALT2 - Y	0.083 ± 0.029	2.7
SNooPy - Y	0.063 ± 0.026	2.3
SALT2 - J	0.040 ± 0.028	1.4
SNooPy - J	0.020 ± 0.025	0.7
SALT2 - H	0.117 ± 0.034	3.3
SNooPy - H	0.097 ± 0.032	2.9
SALT2 - any $YJHK_s$	0.061 ± 0.026	2.3
SNooPy - any $YJHK_s$	0.041 ± 0.022	1.7
SALT2 - JH	0.093 ± 0.029	3.1
SNooPy - JH	0.073 ± 0.026	2.7
SALT2 - YJH	0.096 ± 0.031	3.0
SNooPy - YJH	0.076 ± 0.029	2.6

Table 2. GP NIR max subsets have smaller intrinsic scatter than optical SALT/SNooPy *BVR* at up to ~2-3σ for $\sigma_{v,pec}$ =150km/s.

Conclusions

NIR SN Ia LCs without LC shape or dust corrections are *better* standard candles than optical LCs with those corrections. NIR LCs at NIR max are *as good or better* as standard candles than when referenced to B-max. NIR data are also less sensitive to systematics from dust and intrinsic color variation. Our high-z RAISIN program on HST will exploit this promising infrared approach to limit systematic errors when measuring the expansion history of the universe and making inferences about dark energy (**RAISIN**: Tracers of cosmic expansion with **SN IA** in the **IR**, PI: R. Kirshner, HST GO-13046, GO-14216). NIR SN Ia are thus very promising tools for next generation cosmology studies with HST, JWST, WFIRST.